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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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INVESTIGATION AT ZERO FORWARD SPEED OF A LEADING-EDGE SLAT AS A LONGITUDINAL CONTROL DEVICE FOR VERTICALLY RISING AIRPLANES THAT UTILIZE THE REDIRECTED-SLIPSTREAM PRINCIPLE

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SUMMARY

An investigation of a leading-edge slat as a possible longitudinal control device for vertically rising airplanes that utilize the redirected-slipstream principle has been conducted at zero forward speed in a static-thrust facility at the Langley Aeronautical Laboratory. A semispan wing model equipped with large-chord slotted flaps and two large-diameter overlapping propellers was used in the investigation.

The results indicate that a leading-edge slat can provide increments of pitching moment of the order of those required for control and change in trim with center-of-gravity travel for a vertically rising airplane in hovering flight. In the ground-effect region, however, the slat is generally ineffective as a longitudinal control device. Slat positions above the wing chord plane are preferable to positions below the wing chord plane. The slat also achieved an appreciable reduction in the adverse effect of the ground on the effectiveness of the slotted-flap wing configuration in redirecting propeller slipstreams downward.

INTRODUCTION

Recent work on wing configurations designed to redirect propeller slipstreams downward has demonstrated that this principle can be used to provide direct lift for vertical take-off and landing for configurations, such as transports, with which it is desirable to keep the fuselage approximately horizontal at all times. The flying qualities of vertically rising airplanes in hovering, take-off, forward flight, and landing are being investigated by the Langley Free-Flight Tunnel Section, and a force-test program aimed at developing simple wing configurations that can satisfactorily redirect the slipstream is being conducted by the Langley 7- by 10- Foot Tunnels Branch.

Longitudinal control of the free-flight tunnel model (ref. 1) has been achieved by use of flap-type controls on the trailing edge of the wing. These controls were weak for the low-wing configuration used and they would be expected to be almost completely ineffective for a high-wing configuration where the moment arm from the center of gravity to the control surface would be reduced. Also, with other wing configurations, such as the slotted-flap configuration presented in reference 2, where the trailing-edge surfaces are used to aid in turning the slipstream, the trailing-edge surface would probably be inadequate as a control device.

The present investigation was undertaken, therefore, to study the possibility of using a leading-edge slat, operating in the propeller slipstream ahead of the wing, as a longitudinal control device.

SYMBOLS

The positive sense of forces, moments, angles, and distances is indicated in figure 1. The symbols used in this report are defined as follows:

c	wing chord, ft
$\bar{c}$	mean aerodynamic chord of wing (flap retracted), ft
c_s	slat chord, ft
D	propeller diameter, ft
F	resultant force, lb
h	distance from inboard end of flap trailing edge to ground board, ft
i_w	wing incidence, deg
L	lift, lb
M	pitching moment, ft-lb
T	total propeller thrust, lb
X	longitudinal force (T - Drag), lb
x	longitudinal position of propeller ahead of wing leading edge, ft
z	vertical position of propeller below wing chord plane, ft
δ_f	flap deflection, deg
δ_s	slat deflection, deg

θ turning angle; inclination of resultant-force vector from thrust axis, $\tan^{-1}\frac{L}{X}$, deg

Subscripts:

30 30-percent-chord flaps

60 60-percent-chord flaps

MODEL AND TESTS

A drawing of the model with pertinent dimensions is presented as figure 2 and a photograph of the model mounted for testing is shown as figure 3. The geometric characteristics of the model are given in the following table:

Wing:	
Area (semispan), sq ft	5.125
Span (semispan), ft	3.416
Mean aerodynamic chord, ft	1.514
Root chord, ft	1.75
Tip chord, ft	1.25
Airfoil section	NACA 0015
Aspect ratio	4.55
Taper ratio	0.714
Propellers:	
Diameter, ft	2.0
Nacelle diameter, ft	0.33
Airfoil section	Clark Y
Solidity (each propeller)	0.10

The ordinates of the flaps were derived from the slotted flap 2-h of reference 3 and are presented in table I. The slotted flaps were supported by external brackets. The leading-edge slat was rolled from 1/8-inch sheet steel to an upper-surface contour that corresponded to the upper surface of the wing back to the 30-percent-chord point. For these tests the upper surface of the wing was not modified as it would have to be in a practical application in order to retract the slat; however, it is believed that this difference would have only a small effect on the results. The slat positions tested are shown in figure 4, and the brackets used to support the slat can be seen in figure 3.

The propellers were operated at a rotational speed of about 6,000 rpm which gave a tip Mach number of 0.58. The speed of each motor was determined by observing a stroboscopic type of indicator, to which was fed the output frequency of a small alternator connected to the motor shaft. Both motors were driven from a common power supply and their speeds were usually matched within 10 rpm.

The motors were mounted inside aluminum-alloy nacelles by means of strain-gage beams so that the propeller thrust and torque could be measured. The total lift, longitudinal force, and pitching moment of the model were measured on a strain-gage balance at the root of the wing.

The tests to determine the effects of propeller location were conducted with a setup similar to that shown in figure 5. For these tests, a single propeller was located at the same spanwise location as the inboard propeller shown in figure 2. In computing the data from these tests, the propeller thrust was included in order to make the results comparable with those obtained with the propeller mounted on the wing. The propeller normal force and pitching moment were considered to be negligible (ref. 4).

The ground was simulated by a sheet of plywood as shown in figure 3. All tests with the ground board were conducted with an angle of 20° between the ground board and the thrust axis of the propellers. Because the wing was tapered, the height above the ground was defined as the distance from the inboard end of the flap trailing edge to the ground board. The ground board was removed for the tests out of the ground-effect region.

The investigation was conducted in a static-thrust facility (fig. 3) at the Langley Aeronautical Laboratory. This facility has a useful test space of about 18 by 42 feet in plan and 10 feet in height. All data presented were obtained at zero forward velocity with a thrust of 15 pounds from each propeller. Inasmuch as the tests were conducted under static conditions in a large room, none of the corrections that are normally applicable to wind-tunnel tests were applied. The effects of slat position, slat deflection, flap deflection, propeller location, and proximity to the ground were investigated.

RESULTS AND DISCUSSION

In order to evaluate the effectiveness of a longitudinal control device such as a leading-edge slat, it is necessary to have some indication of the change in pitching moment required for control and trim. An indication of the control required in hovering can be obtained from the data of reference 5 where the amount of pitching-moment control used in flying this model corresponds to a value of M/TD of ± 0.02. Comparison of the pitching moment of inertia of the model of reference 5 with that of existing multiengine transports indicates that the model moment of inertia was representative of practical airplanes. Thus, the pitch control used $(M/TD = \pm 0.02)$ can serve as a crude yardstick in evaluating the effectiveness of a leading-edge slat.

The amount of pitching moment required to accommodate changes in center-of-gravity location with changes in airplane loading depends on the details of the airplane design; however, examination of several possible vertically rising airplane designs indicates that a value of M/TD of about 0.08 would be adequate if relatively large-diameter propellers are used. If a leading-edge slat is to provide the functions of both control and trim for center-of-gravity travel, then it must supply an increment of M/TD of about 0.12.

Effect of Slat Position

The effects of position and deflection of the leading-edge slat on the characteristics of the original model out of the ground-effect region are shown in figures 6 and 7. In general, slat positions above the wing are preferable in that they give some control over pitching moments with only small changes in turning angle. Some loss in resultant force is indicated, however.

The slat positions below the wing (fig. 7) do not appear desirable because, in addition to the loss in resultant force, they also exhibit a serious loss in turning angle. The large changes in pitching moment shown for slat positions D and H result from the large losses in turning angle shown for these positions and are therefore not significant. It should be kept in mind that these results are for the configuration with the thrust axis on the wing chord plane. Some unpublished results have indicated that, for a configuration in which the thrust axis is far below the wing chord plane, the use of a slat or vane in a low and rearward position may effect some improvement in turning characteristics.

The characteristics of the model near the ground with the slat mounted in various positions above the wing are shown in figure 8. With the model near the ground, the slat can appreciably increase the turning angle.

Examination of the pitching-moment data indicates that, out of the ground-effect region, the increment of pitching moment $(M/TD = 0.12)$ required for control and center-of-gravity travel can be obtained with a leading-edge slat mounted above the wing (fig. 6). The model, however, is still badly out of trim and the moment reference point would have to be moved rearward to about the 60-percent-chord point to counteract the large out-of-trim diving moments. Also, near the ground (fig. 8) the slat is totally inadequate as a control device.

Inasmuch as the slat contributes to the pitching moments through the effect that the slat has on the flow over the wing as well as by the direct forces on the slat, there exists the possibility that the slat may exhibit lag when used as a control device. The leading-edge slat as used herein is similar to the controllable auxiliary airfoils of reference 6, which were used as ailerons and gave indications of lag, although no lag measurements were made. The two configurations are not directly comparable, however, and definite conclusions cannot be drawn. Further development of the leading-edge slat as a longitudinal control device for vertically rising airplanes should include an investigation of lag and of the division of loads between the slat and the wing.

Effect of Propeller Position

The data of reference 4 indicate that lowering the thrust axis of the propellers below the wing chord plane can be beneficial both in reducing the diving moments and in reducing the adverse effects of the ground. The effects of propeller position on the characteristics of the model with the slat mounted in position G were therefore investigated. For convenience in changing the propeller position, the tests were conducted by using only the inboard motor, which was mounted on an auxiliary stand as shown in figure 5. The effects of changing vertical position of the propeller are shown in figure 9 and the effects of changing longitudinal position are shown in figure 10.

Lowering the thrust axis below the wing chord plane (fig. 9) produced the expected reduction in the diving moments. A position 0.125D below the wing chord plane, in addition to effecting some reduction in diving moments, also gave a slight gain in turning angle. Further lowering of the thrust axis to 0.250D results in a loss in turning angle. The characteristics were relatively insensitive to changes in the longitudinal position of the propeller (fig. 10).

Characteristics of the Modified Model

The original configuration does not appear to redirect the slipstream adequately inasmuch as for hovering, even out of the ground-effect region, a nose-up attitude of about 30° would be required. Near the ground, somewhat higher attitudes would be required even with a leading-edge slat. Also, both in and out of the ground-effect region, large diving moments must be dealt with. Figure 9 indicates that lowering the thrust axis can effect some increase in the turning angle and a decrease in the diving moments. Also, reference 2 indicates that incorporating incidence between the wing chord plane and the thrust axis could increase the turning angle. Accordingly, these modifications (5° incidence and the thrust axis lowered 0.100D) were incorporated into the model.

The turning characteristics of the modified model out of the ground-effect region are presented in figure 11. It will be noted that the deflection of the front flap has been increased to 60°. Comparison of the data of figure 6 and figure 11 indicates that the expected reduction in diving moments was realized. However, with the slat off, a turning angle of 65° and a resultant force of only 85 percent of the thrust was achieved. Similar disappointing results for the modified model were noted in reference 4. Tuft studies indicated that the flow was separating from the rear ends of the nacelles and it may be possible that this separation was contaminating the flow through the slots. Attempts to reduce the separation were unsuccessful because the length of the electric motors used to drive the propellers did not leave adequate length in which to fair out the nacelles.

The effect of the slat is also shown in figure 11 for several mounting positions. In general, deflection of the slat caused a loss in both turning angle and resultant force. As with the original model, however, the diving moments have been appreciably reduced by the deflection of the slat. With a slat deflection of 20°, the model would be trimmed with the center of gravity located at the 40-percent-chord point. At position A the slat is almost out of the propeller slipstream and therefore not very effective. It is interesting to note that, at position B, linear pitching-moment characteristics were obtained up to a slat deflection of 46°. At these high deflections, the slat was completely stalled; however, the drag force on the slat and the effect of the slat on the wing apparently combined to produce linear pitching moments. Deflection of the slat in position C was limited because the trailing edge of the slat hit the nacelle.

The effect of the ground on the characteristics of the model with the slat mounted in position B is presented in figure 12. As was noted with the original configuration (fig. 8), positive deflection of the slat with the modified configuration (fig. 12) reduces the adverse effects of the ground on the turning angle. As a longitudinal control device, however, the slat is generally ineffective when the model is in the position closest to the ground.

Comparison of Characteristics With One or Two Propellers

It has previously been noted that the characteristics obtained with the modified model were not as good as expected and that the probable reason for the poor results with the slat off was the flow separation observed on the rear end of the nacelles. A comparison of the characteristics of the model with one and two propellers and with the slat on is presented in figure 13. Although in reference 4 it was shown that, with the slat off and the thrust axis on the chord plane, both the turning angle and the resultant force were better with two propellers operating, figure 13 indicates a similar increase in resultant force but a loss in turning angle with the slat on the modified model. Tuft studies indicated that this loss may be due to the fact that the slat did not extend all the way to the wing tip (fig. 2) because an appreciable amount of propeller slipstream appeared to be escaping past the tip of the slat. Also, the slat tended to flatten and spread the slipstream from the outboard propeller and cause some of the slipstream to spill around the tip of the wing.

Figure 13 also indicates better characteristics for the case with a single propeller independently mounted as compared with the single propeller on the wing. This improvement is due primarily to the effects of flow separation from the nacelle as illustrated in figure 14. When a dummy nacelle having a blunt rear end as shown in the sketch in figure 14 was mounted on the wing behind the propeller, extreme separation was caused and both the resultant force and the turning angle were reduced. Adding a fairing behind the dummy nacelle partly regained the losses due to separation.

CONCLUSIONS

Investigation of the effectiveness of a leading-edge slat as a possible longitudinal control device for vertically rising airplanes that utilize the redirected-slipstream principle indicates the following conclusions:

1. A leading-edge slat can provide increments of pitching moment of the order of those required for control and for changes in trim due to center-of-gravity travel for a vertically rising airplane in hovering flight. In the ground-effect region, however, the slat is generally ineffective as a longitudinal control device.

2. Slat positions above the wing chord plane are preferable to positions below the wing chord plane.

3. A leading-edge slat can appreciably reduce the adverse effects of the ground on the effectiveness of the slotted-flap wing in redirecting slipstreams downward.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 15, 1956.

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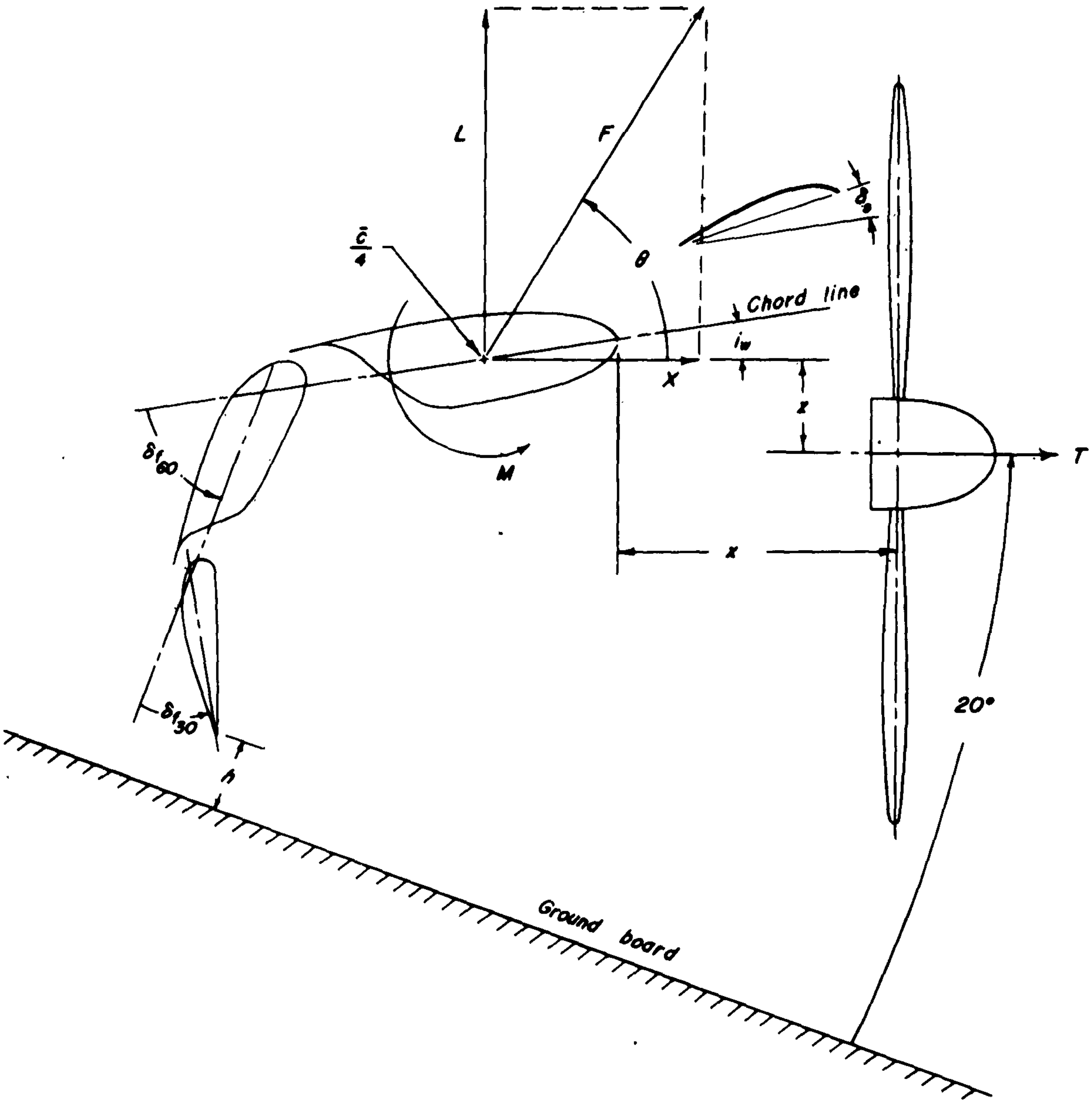

Figure 1.- Convention used to define positive sense of forces, moments, angles, and distances.

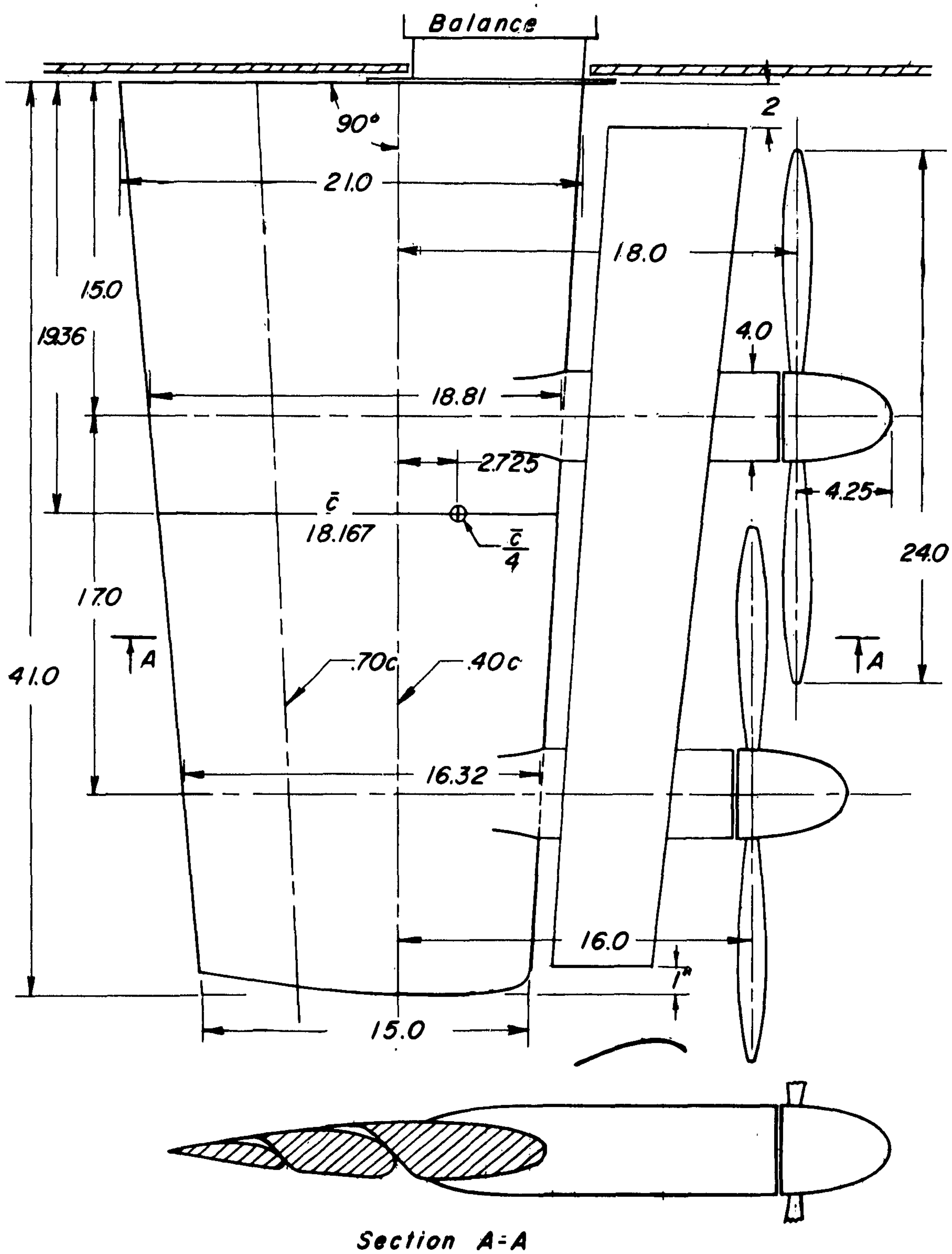

Figure 2.- Sketch of original configuration. All dimensions are in inches.

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Figure 3.- Modified configuration installed on static-thrust stand with ground board in closest position and leading-edge slat in position B. $i_w = 5^{\circ}$; $\frac{z}{D} = 0.100$.

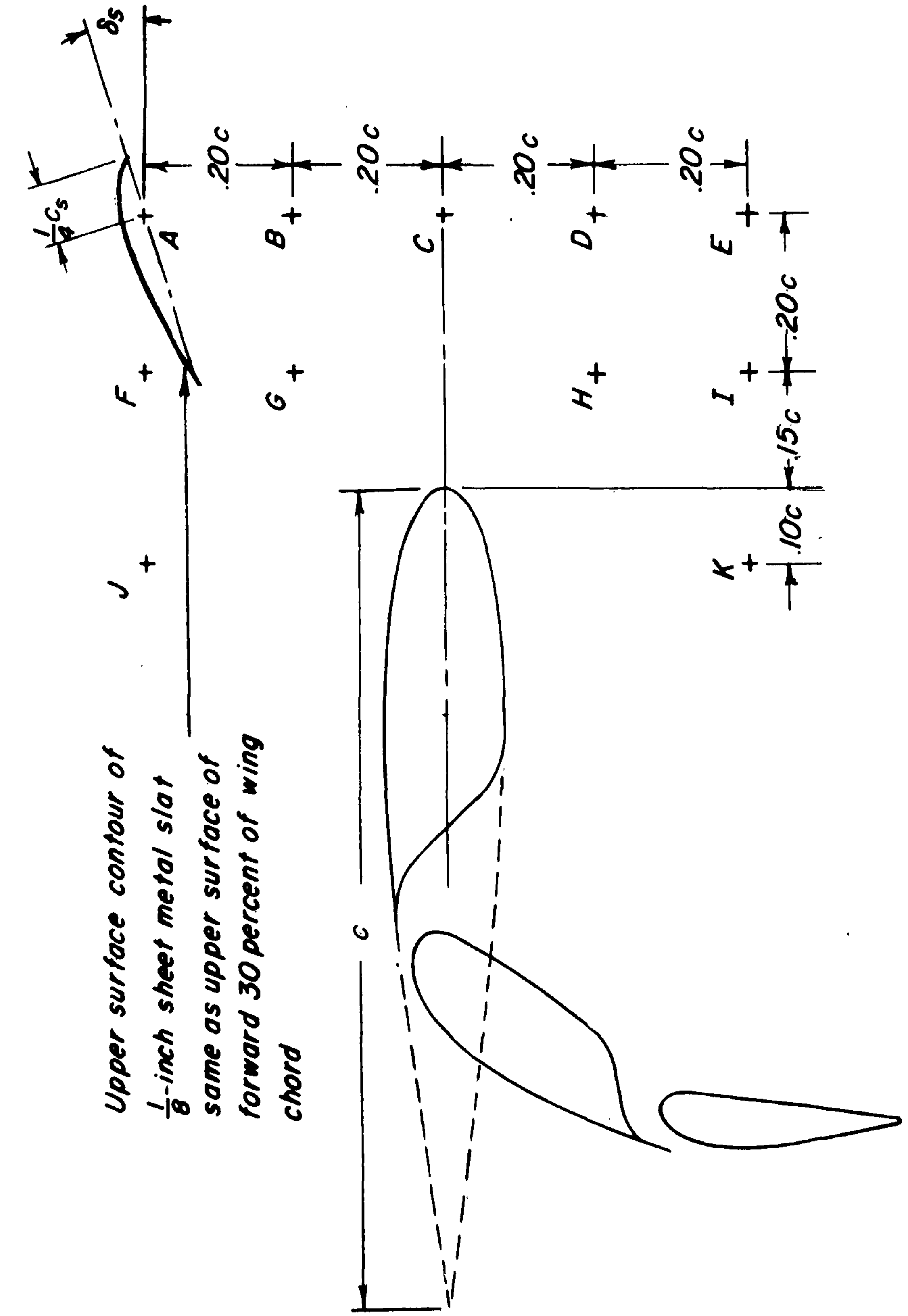

Figure 4.- Slat positions investigated.

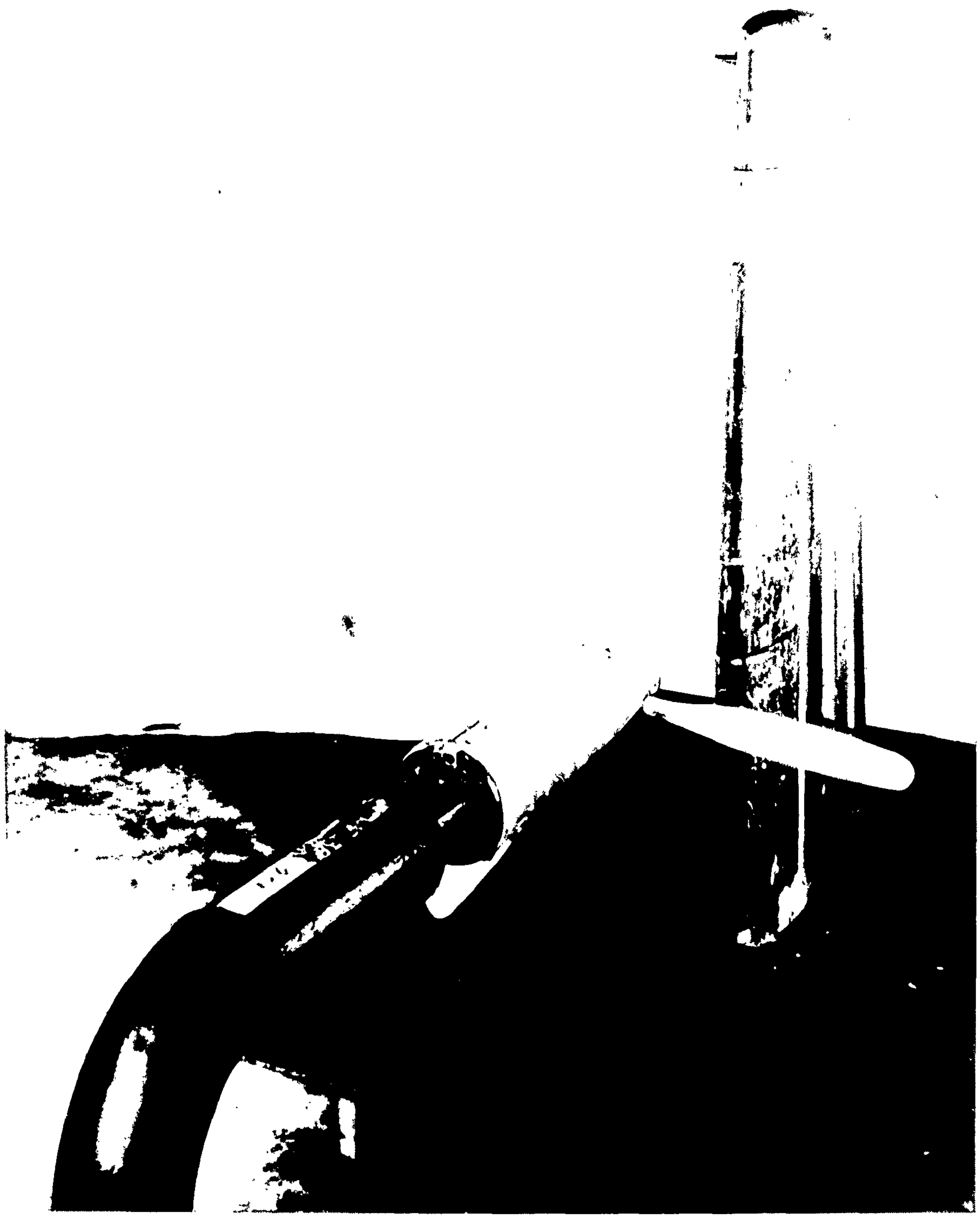

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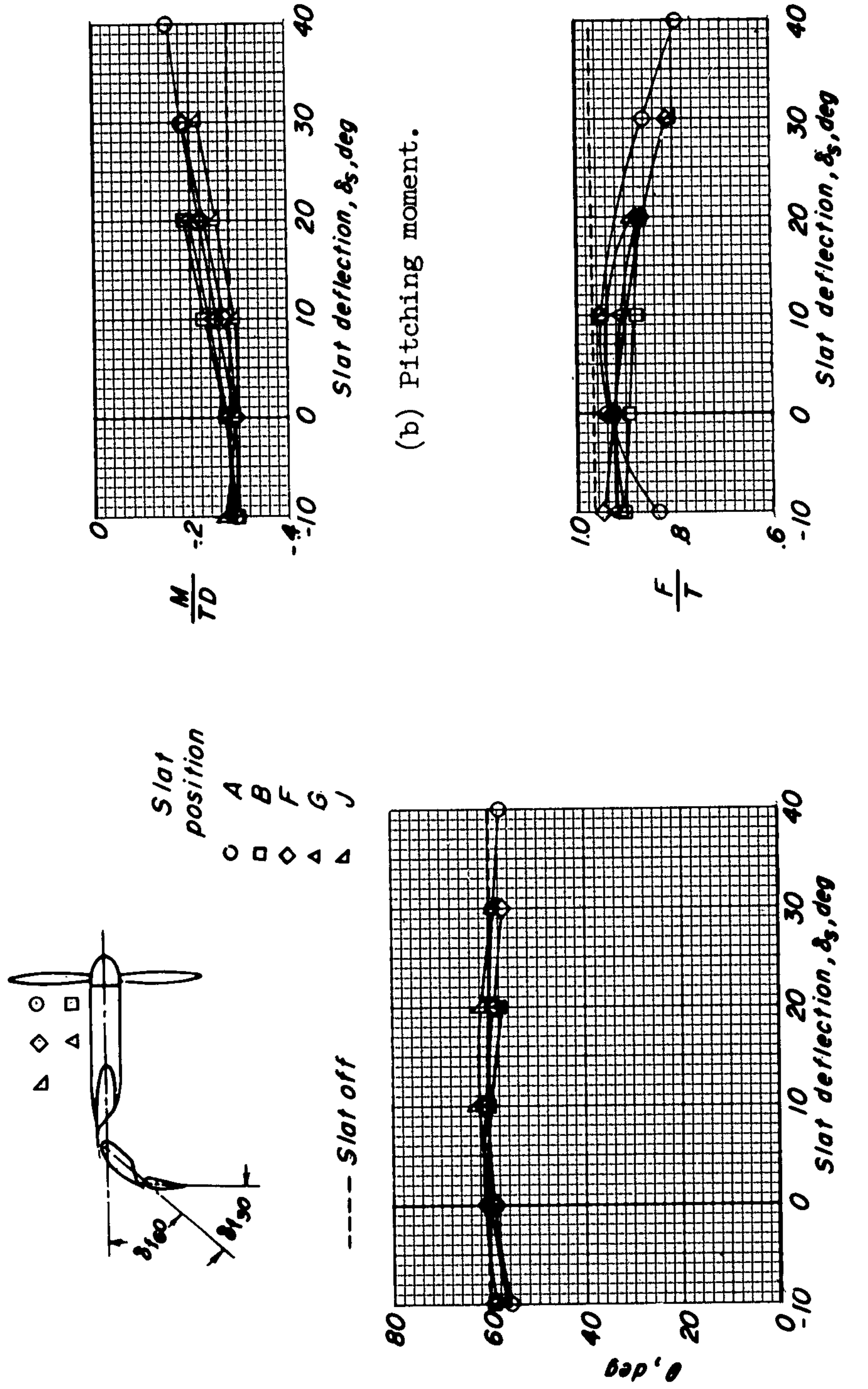
Figure 5.- Static-thrust setup with single propeller independently mounted for tests involving changes in propeller position.

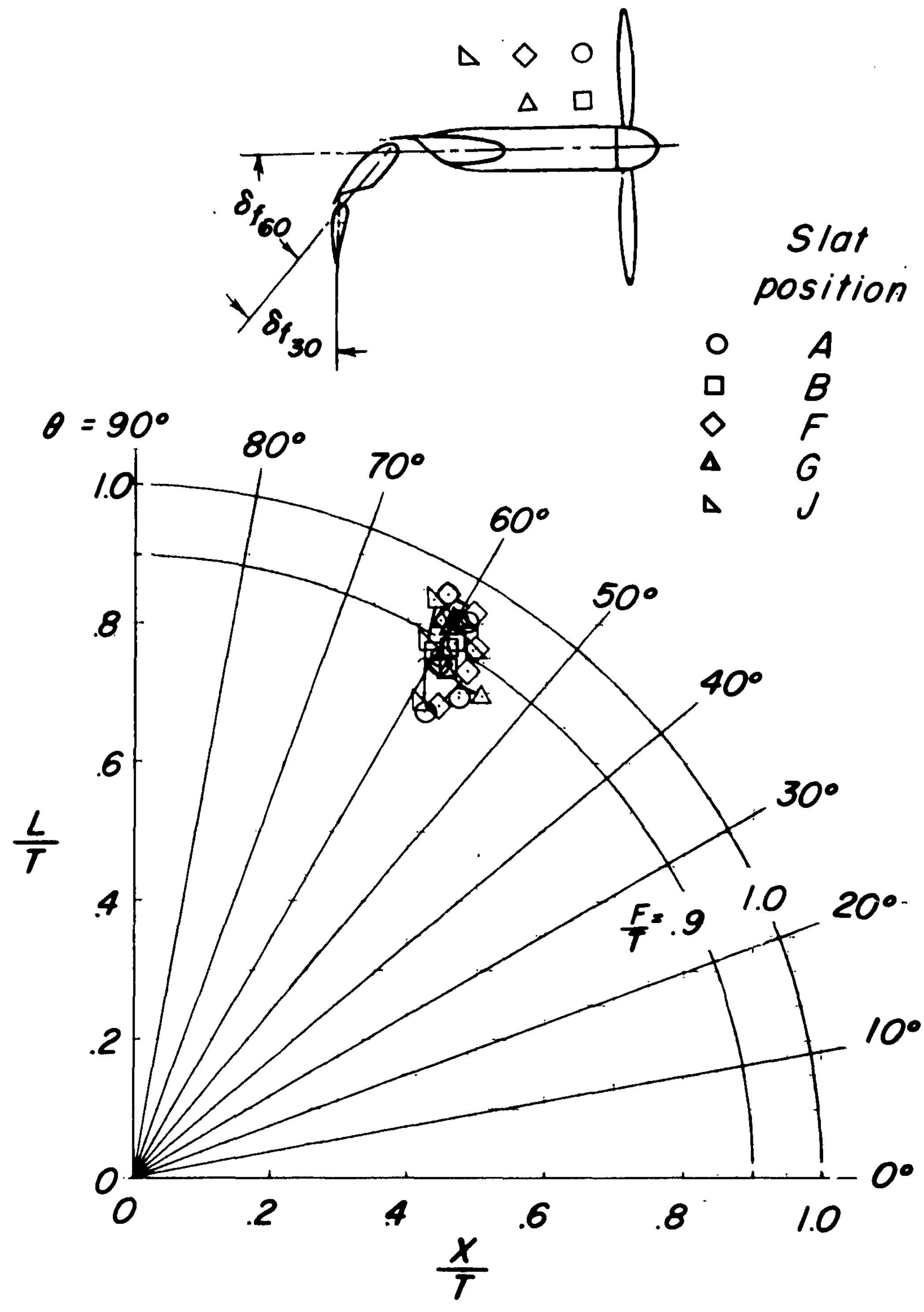


(a) Turning angle.

(b) Pitching moment.

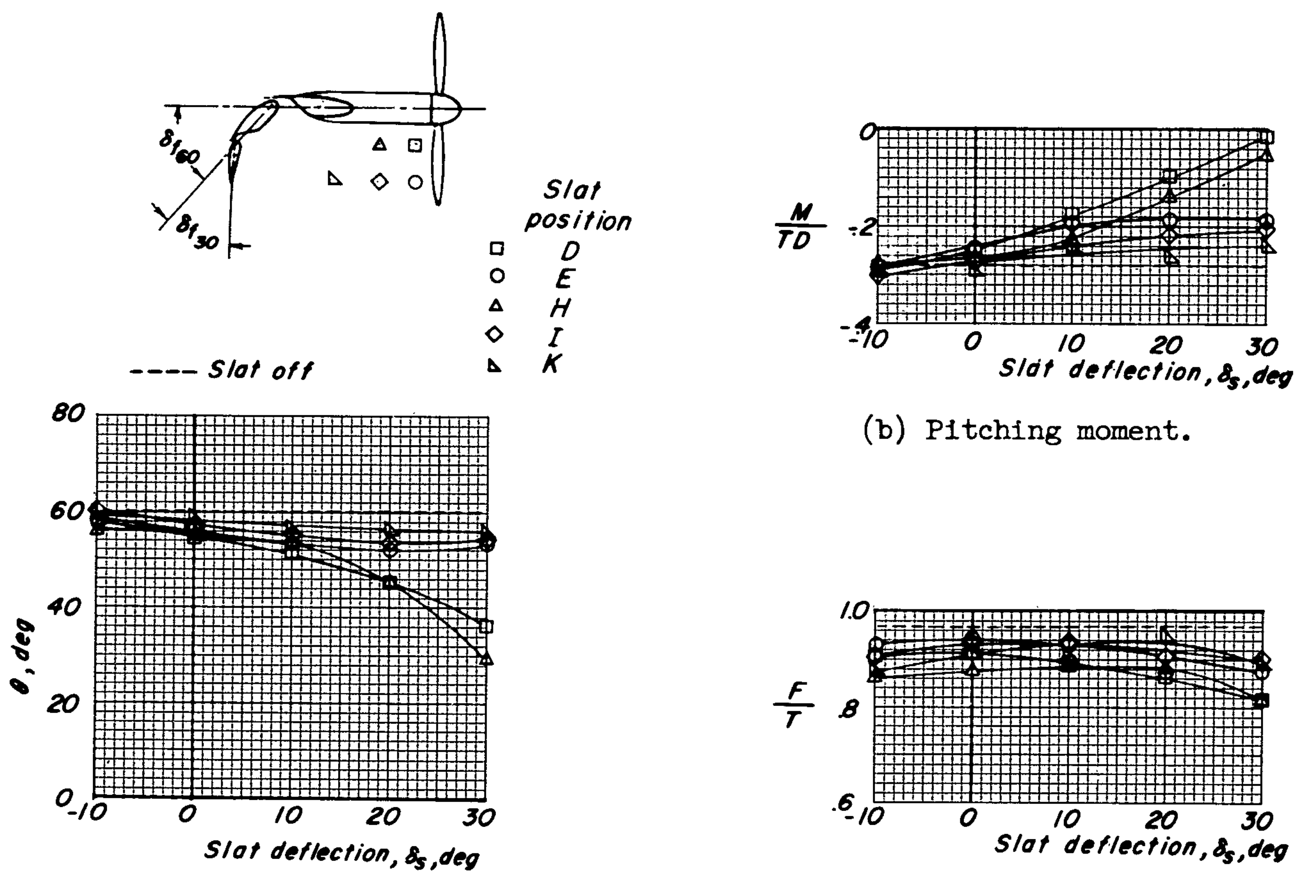
(c) Ratio of resultant force to thrust.

Figure 6.- Effect of slat position and deflection. Out of the ground-effect region; $\delta_{f_{60}} = 50^{\circ}$; $\delta_{f_{30}} = 40^{\circ}$; slat positions above wing; $i_w = 0^{\circ}$.



(d) Summary of turning effectiveness. (δ_s is variable.)

Figure 6.- Concluded.

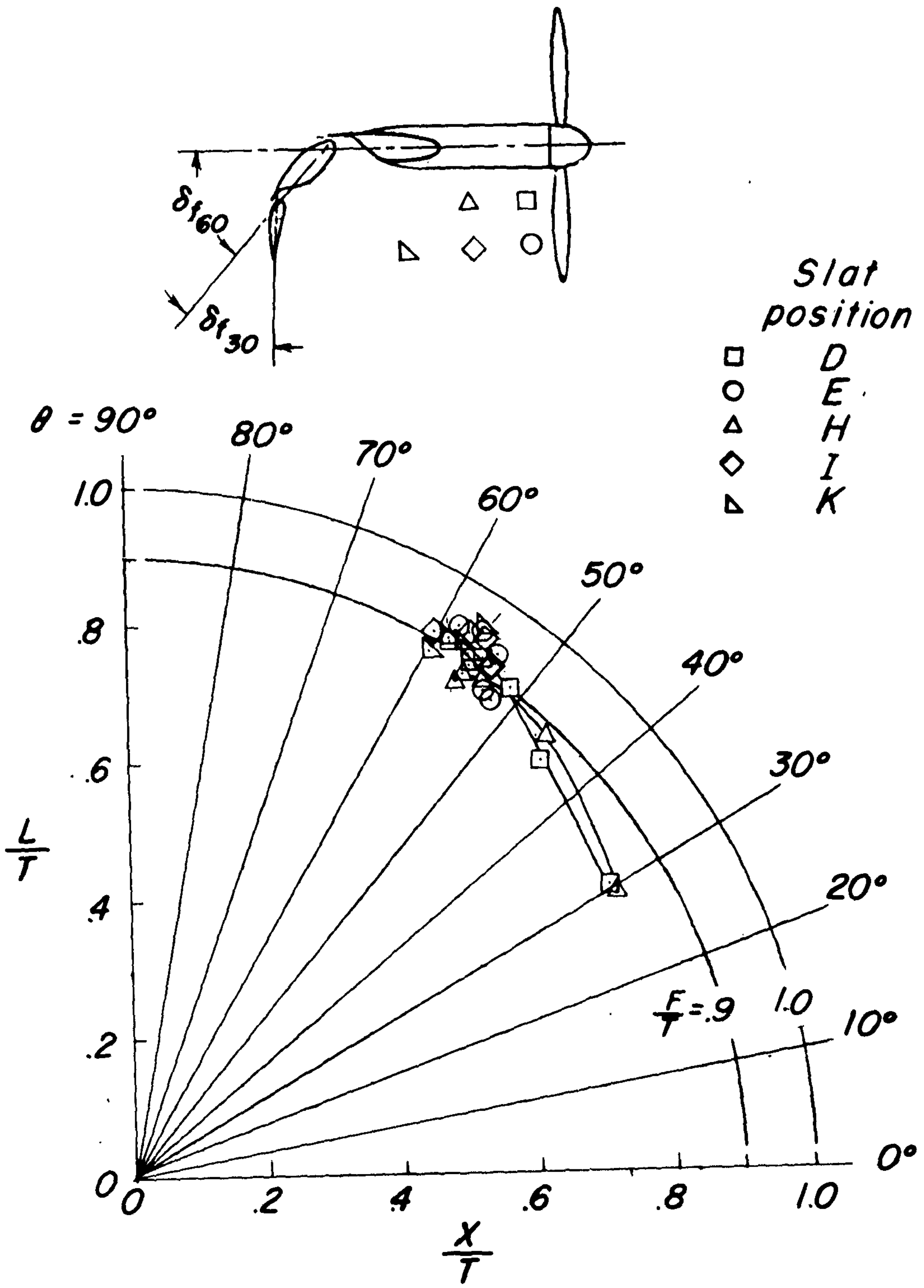


(a) Turning angle.

(b) Pitching moment.

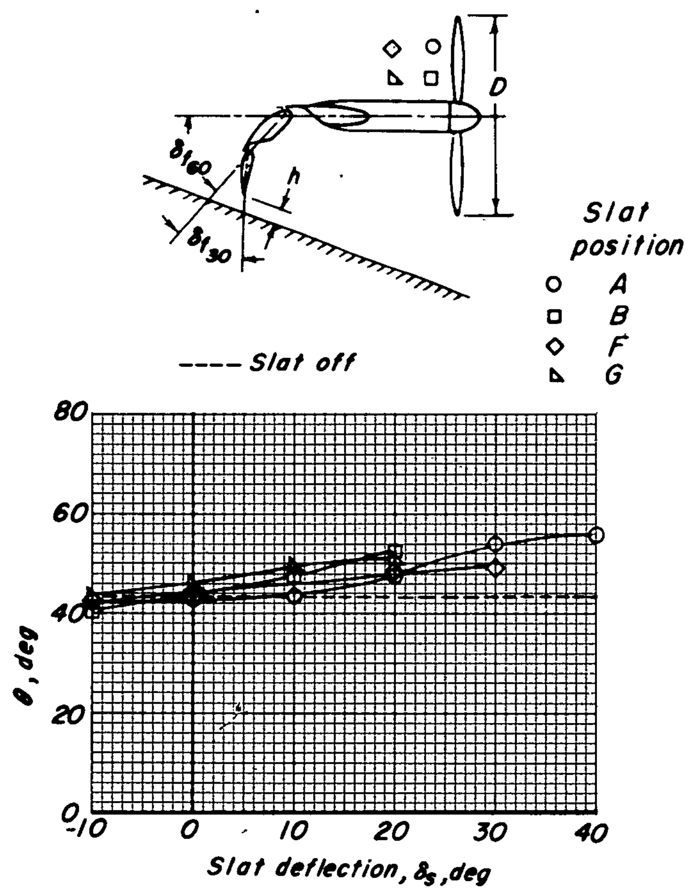
(c) Ratio of resultant force to thrust.

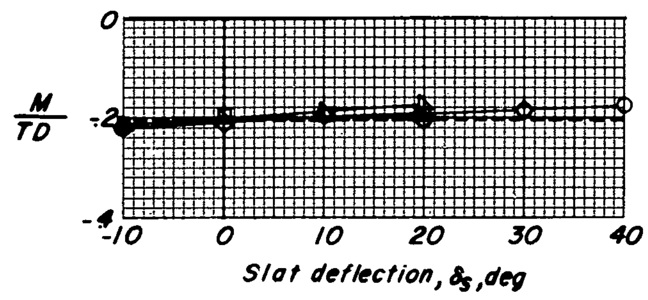
Figure 7.- Effect of slat position and deflection. Out of the ground-effect region; $\delta_{f_{60}} = 50^{\circ}$; $\delta_{f_{30}} = 40^{\circ}$; slat positions below wing; $i_w = 0^{\circ}$.



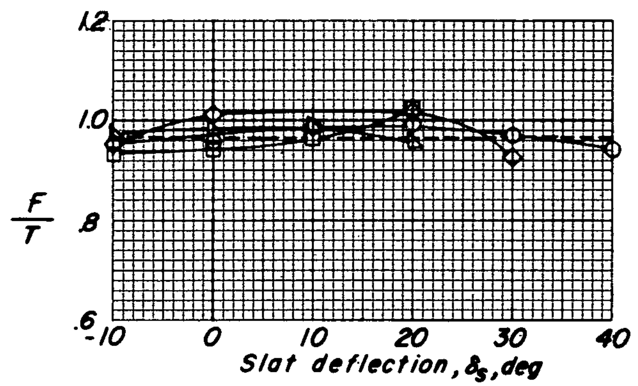
(d) Summary of turning effectiveness. (δ_s is variable.)

Figure 7.- Concluded.





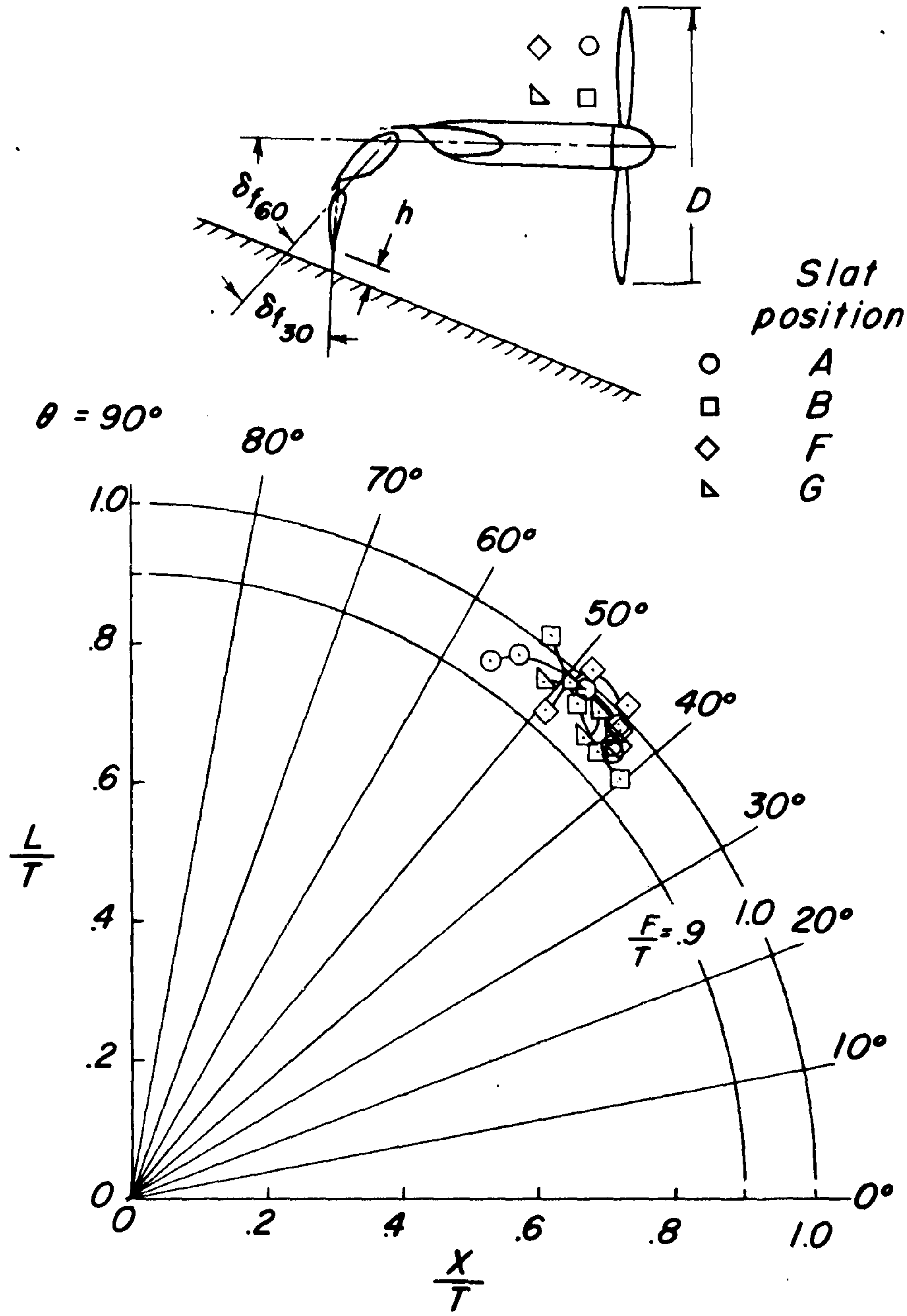
(b) Pitching moment.



(a) Turning angle.

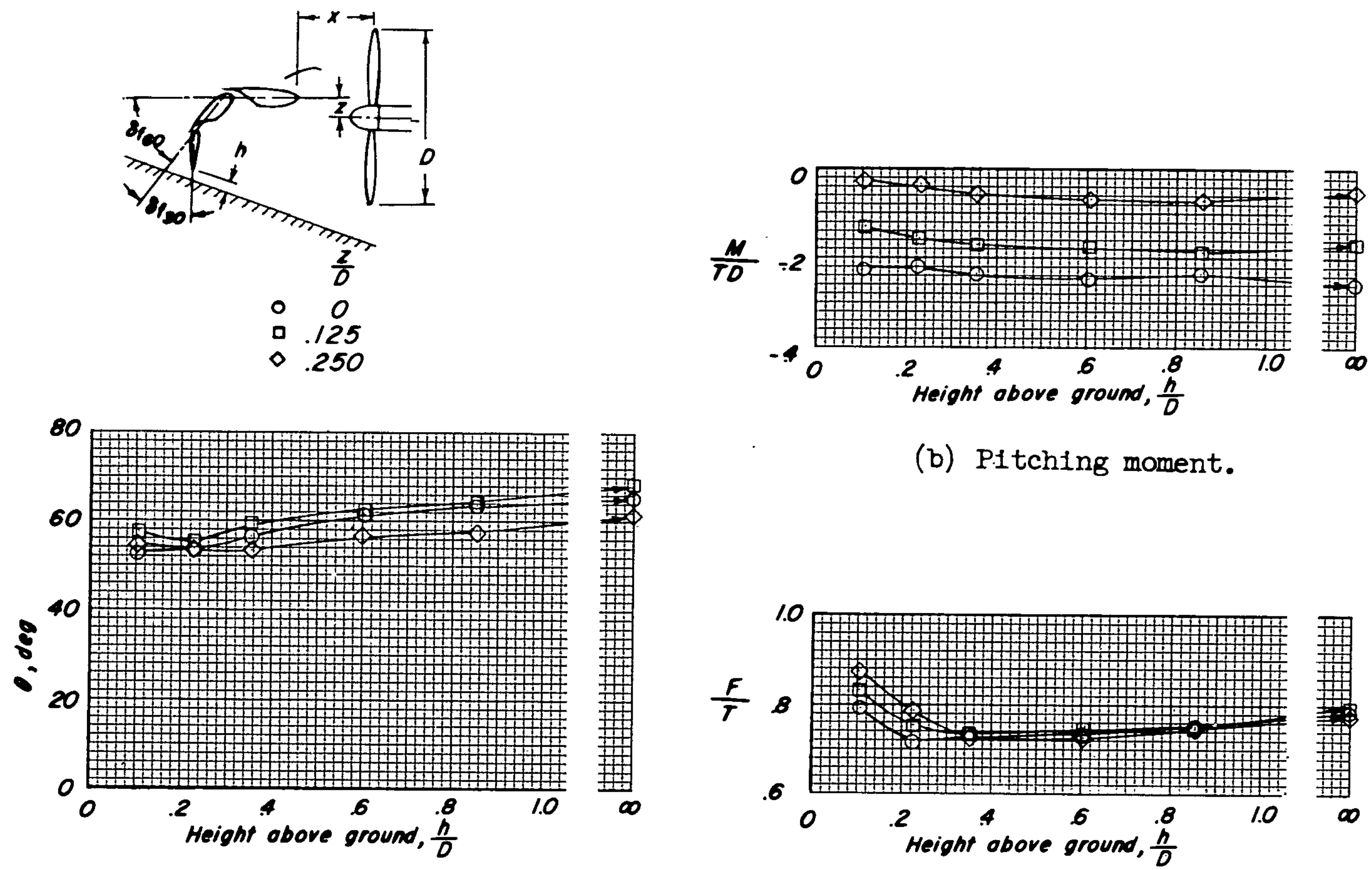
(c) Ratio of resultant force to thrust.

Figure 8.- Effect of slat position. In the ground-effect region; $\delta_{f_{60}} = 50^{\circ}$; $\delta_{f_{30}} = 40^{\circ}$; $i_w = 0^{\circ}$; $\frac{h}{D} = 0.08$.



(d) Summary of turning effectiveness. (δ_s is variable.)

Figure 8.- Concluded.

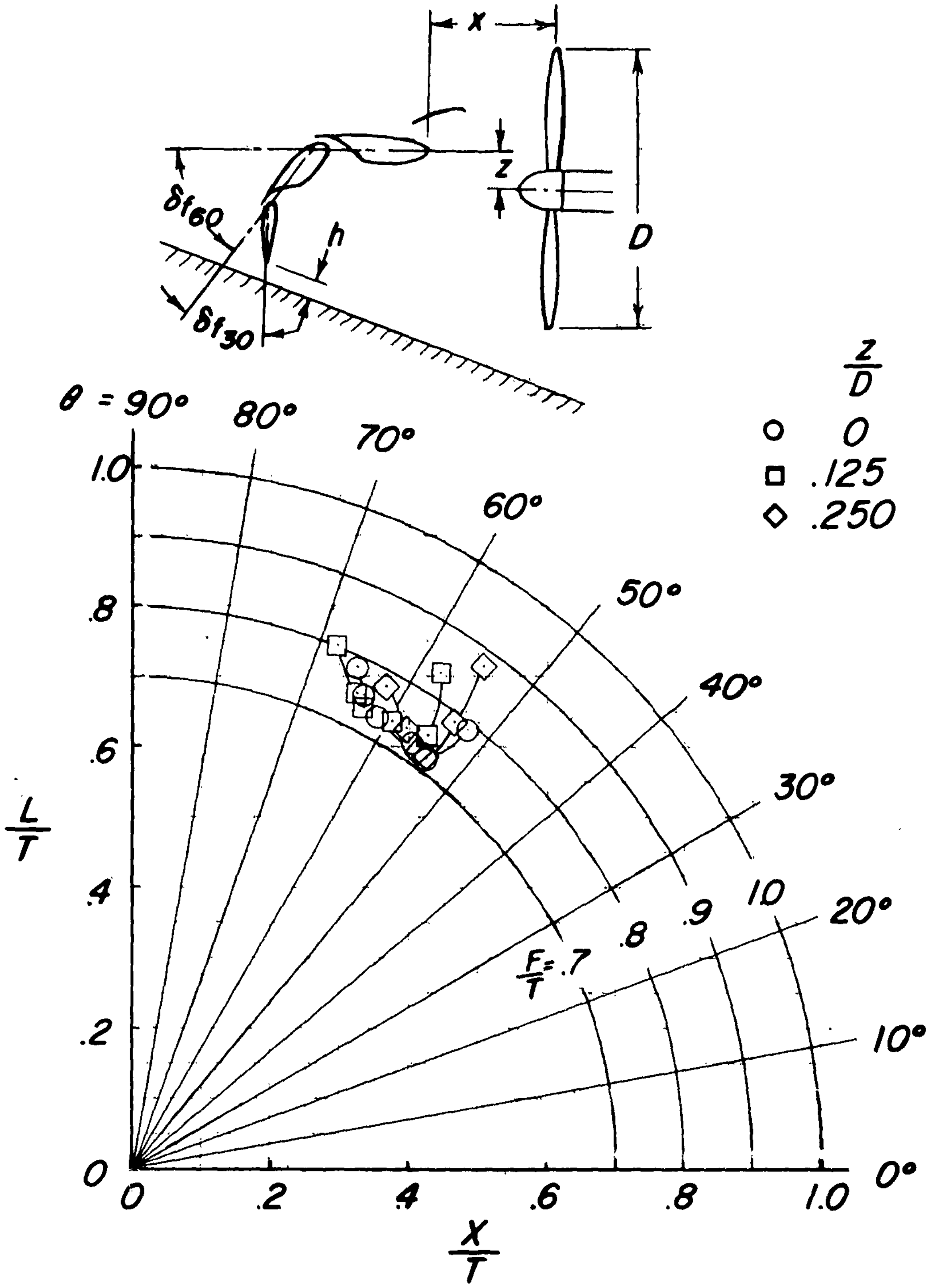


(a) Turning angle.

(b) Pitching moment.

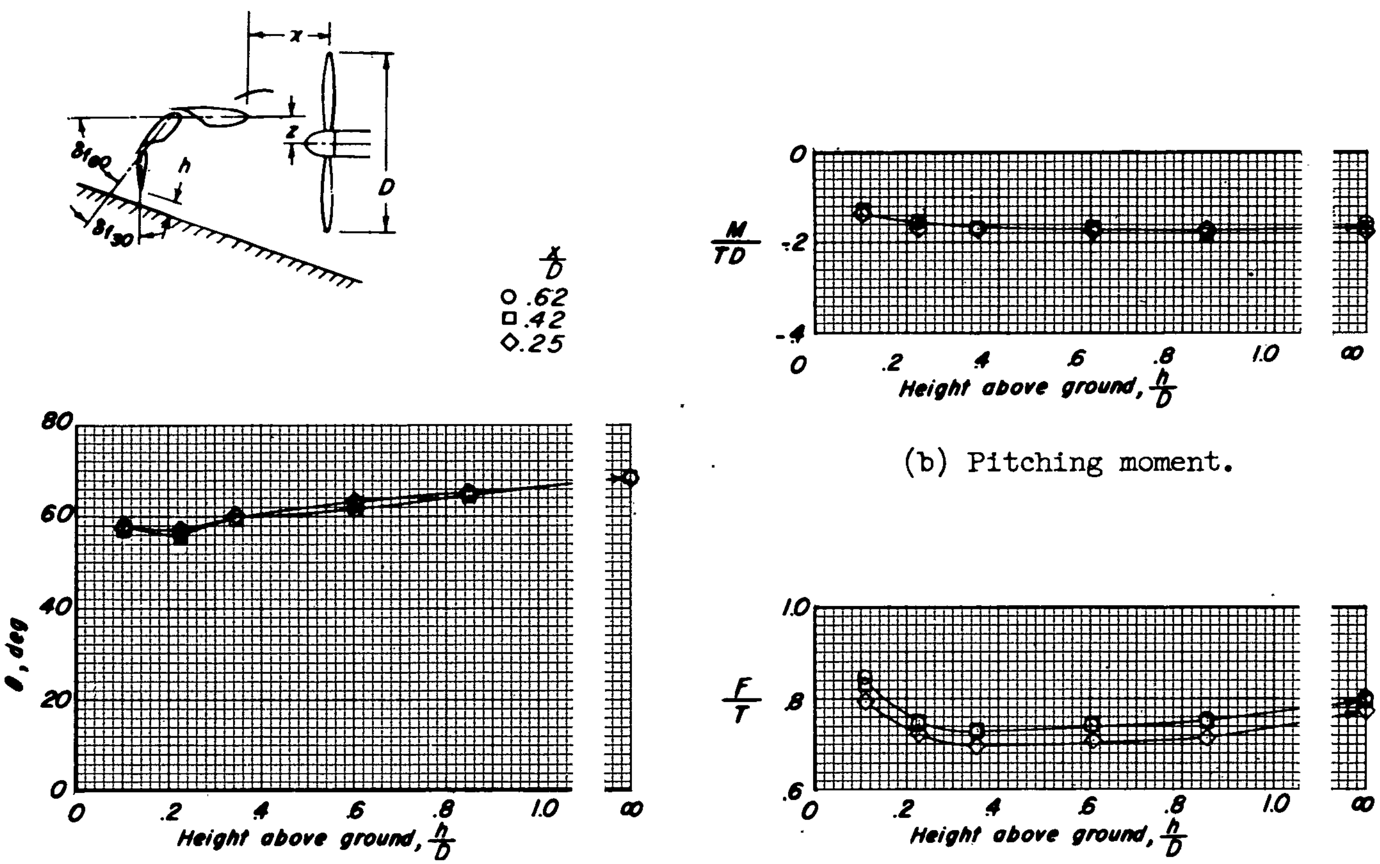
(c) Ratio of resultant force to thrust.

Figure 9.- Effect of vertical position of propeller thrust axis on the variation of characteristics with height above the ground. $\delta_{f_{60}} = 50^{\circ}$; $\delta_{f_{30}} = 40^{\circ}$; slat at position G; $\delta_s = 20^{\circ}$; $i_w = 0^{\circ}$; $\frac{x}{D} = 0.42$.



(d) Summary of turning effectiveness. $\left(\frac{h}{D}\right.$ is variable.$\left.\right)$

Figure 9.- Concluded.

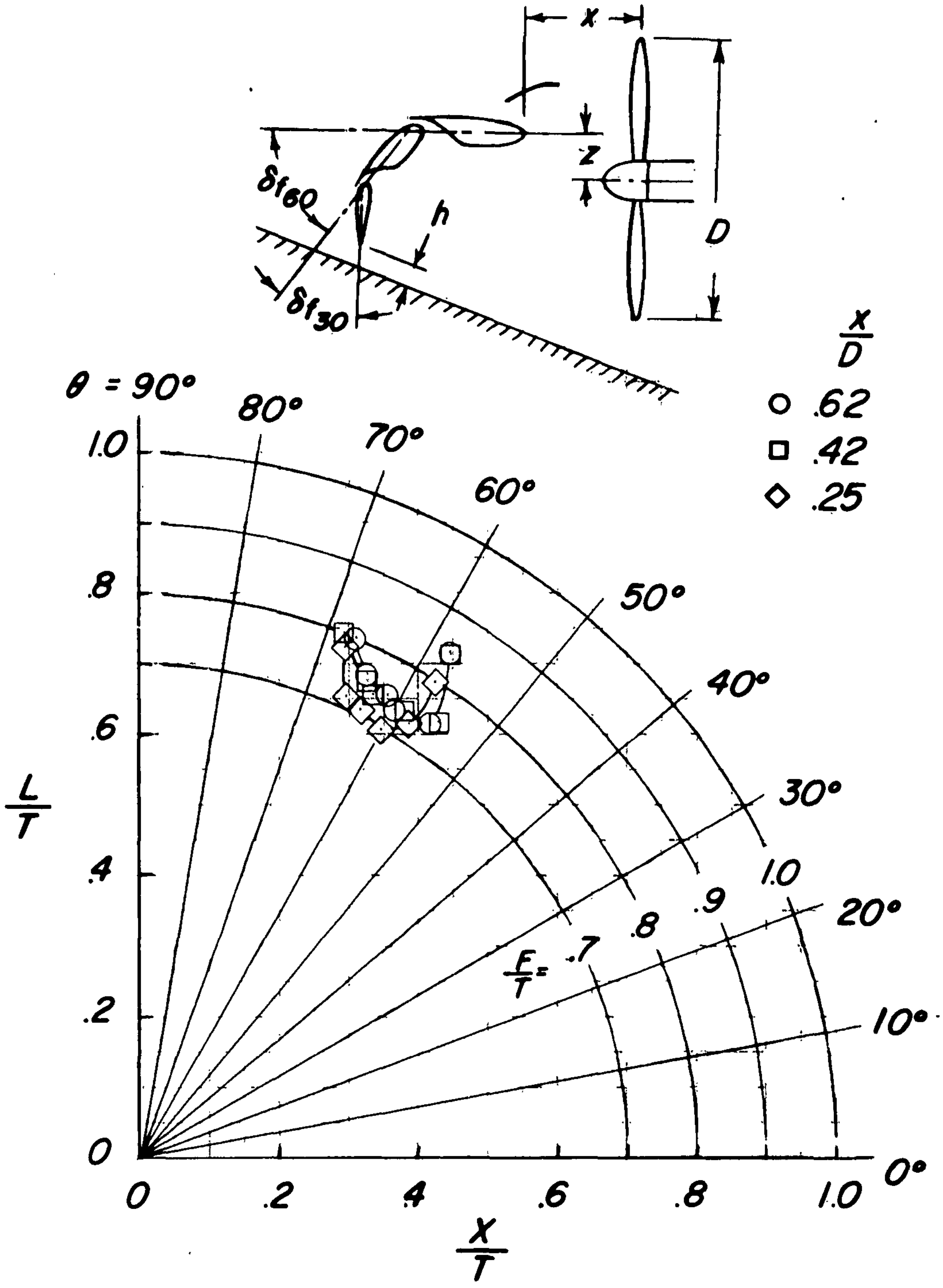


(a) Turning angle.

(b) Pitching moment.

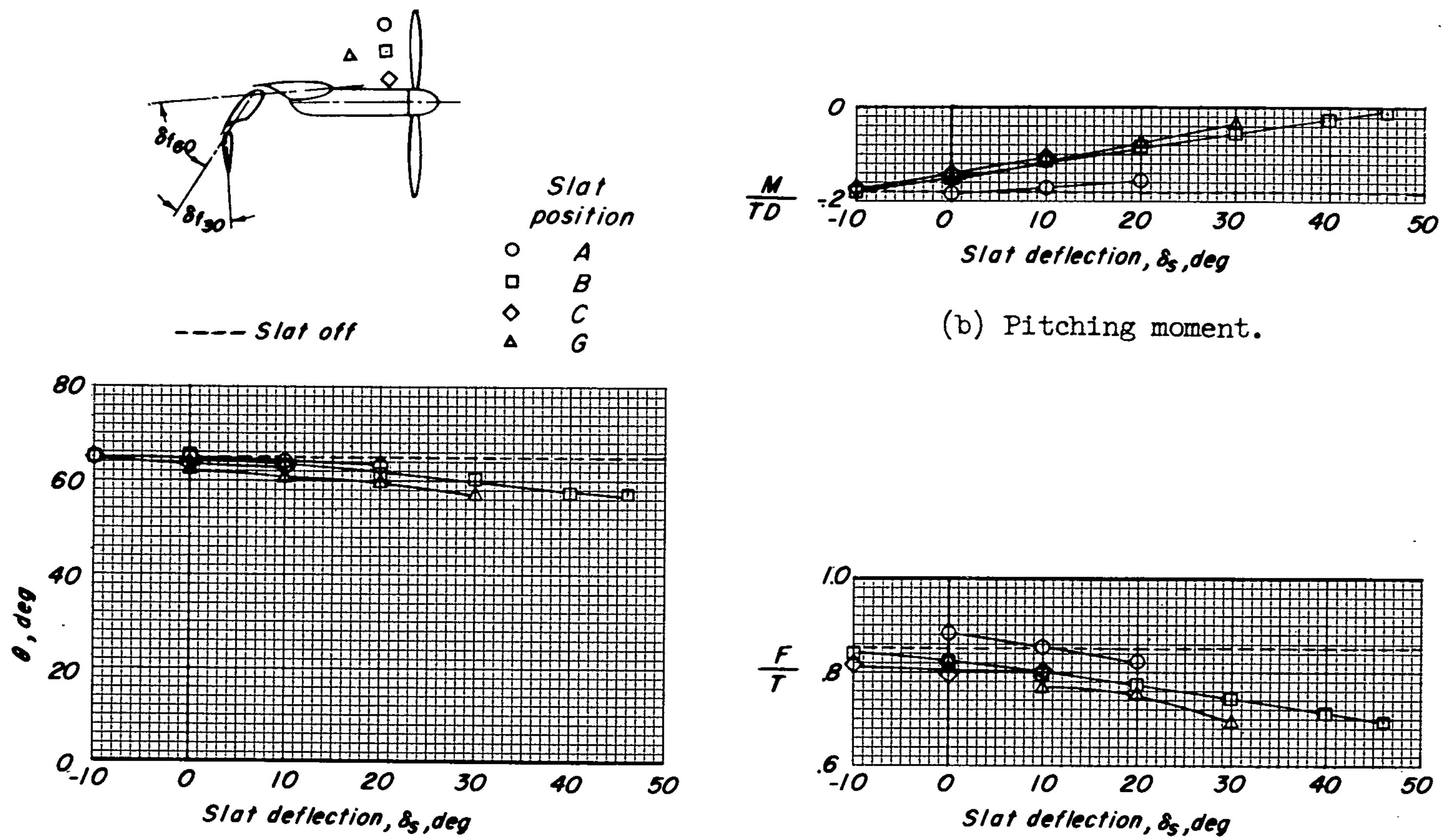
(c) Ratio of resultant force to thrust.

Figure 10.- Effect of longitudinal position of propeller on the variation of characteristics with height above the ground. $\delta_{f_{60}} = 50^\circ$; $\delta_{f_{30}} = 40^\circ$; slat at position G; $\delta_s = 20^\circ$; $i_w = 0^\circ$; $\frac{z}{D} = 0.125$.



(d) Summary of turning effectiveness. $\left(\frac{h}{D}\right.$ is variable.$\left.\right)$

Figure 10.- Concluded.

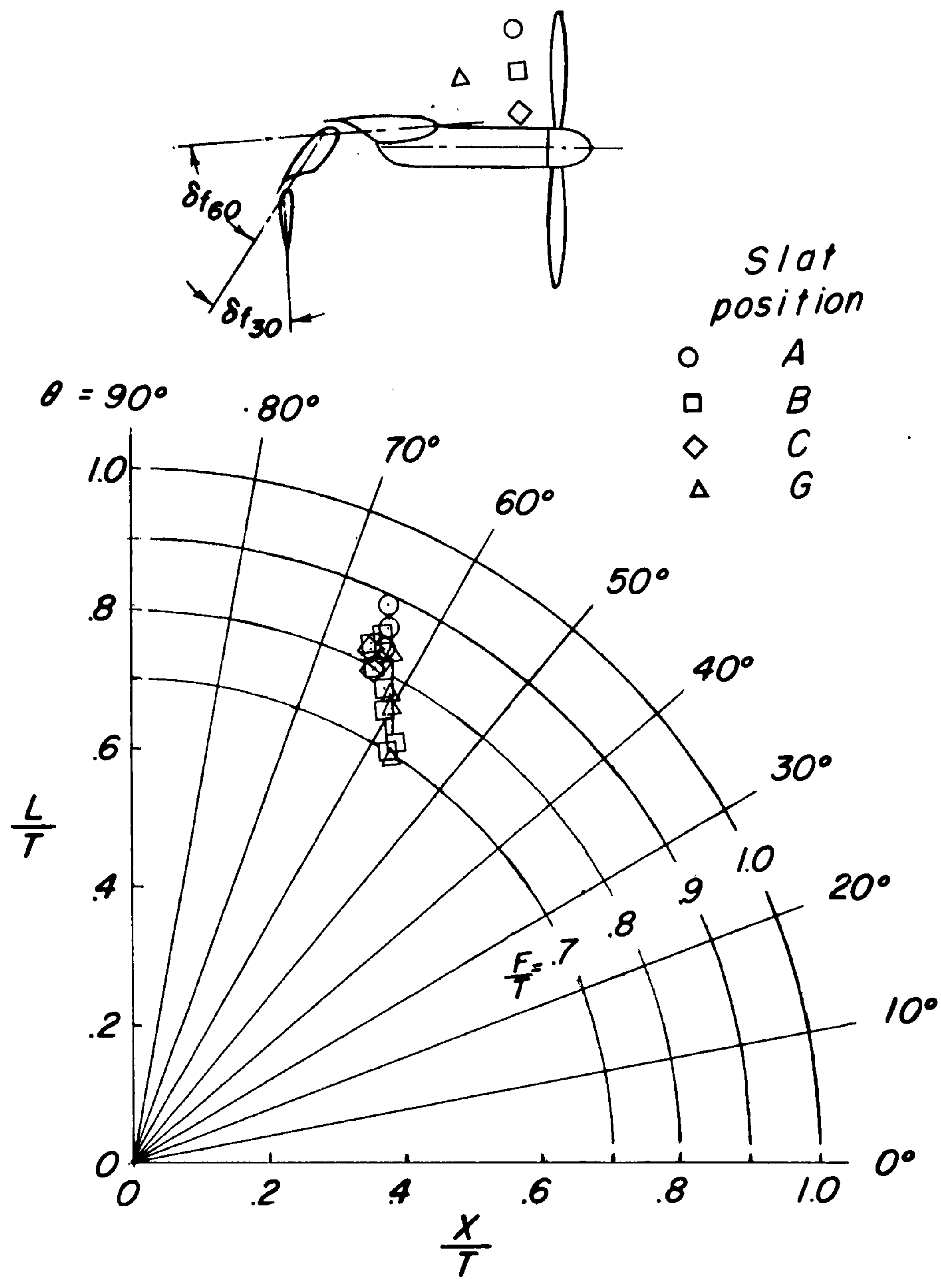


(a) Turning angle.

(b) Pitching moment.

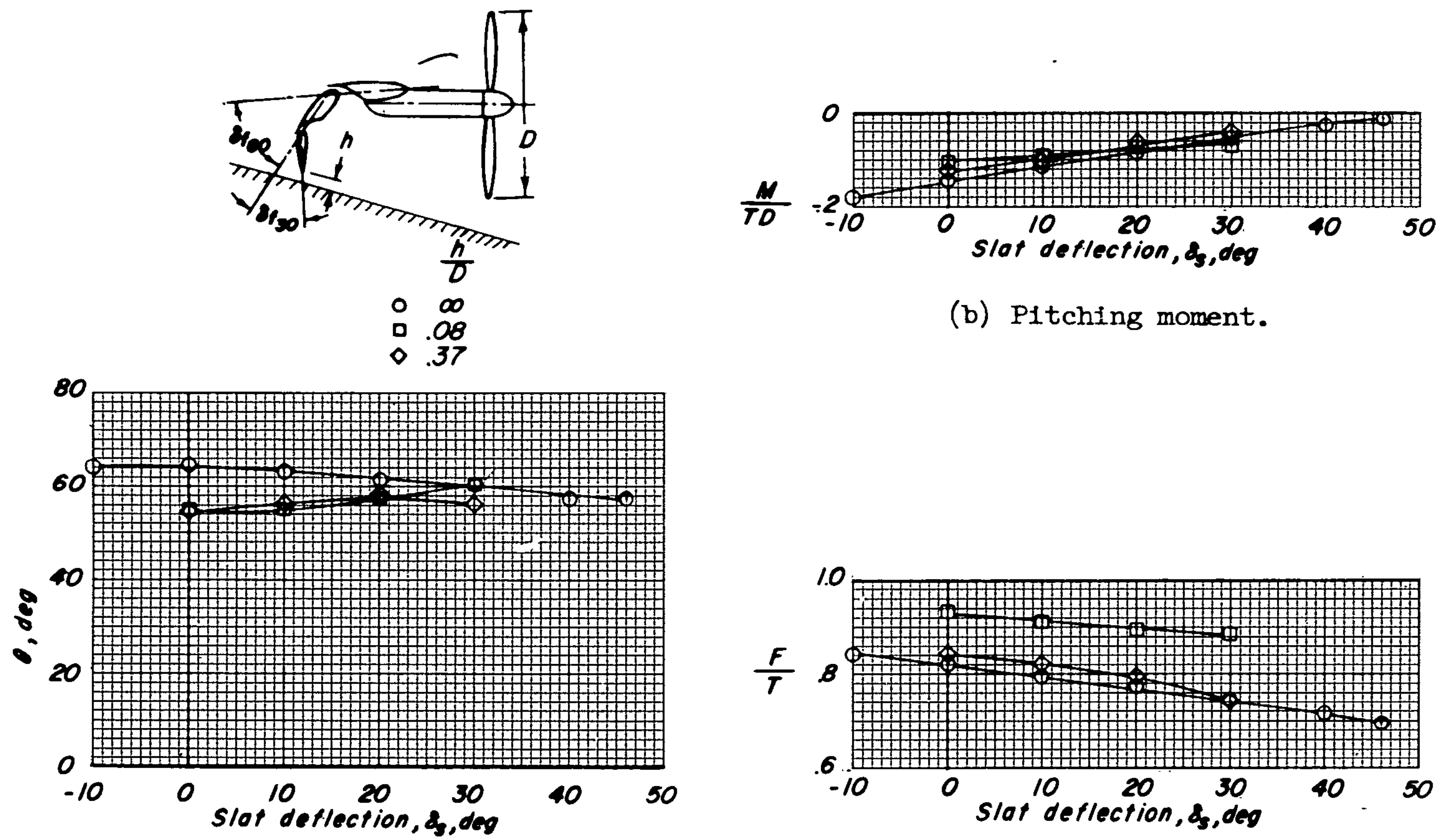
(c) Ratio of resultant force to thrust.

Figure 11.- Effect of slat position and deflection on characteristics of revised model out of the ground-effect region. $\delta_{f_{60}} = 60^\circ$; $\delta_{f_{30}} = 40^\circ$; $i_w = 5^\circ$; $\frac{z}{D} = 0.100$.



(d) Summary of turning effectiveness. (δ_s is variable.)

Figure 11.- Concluded.

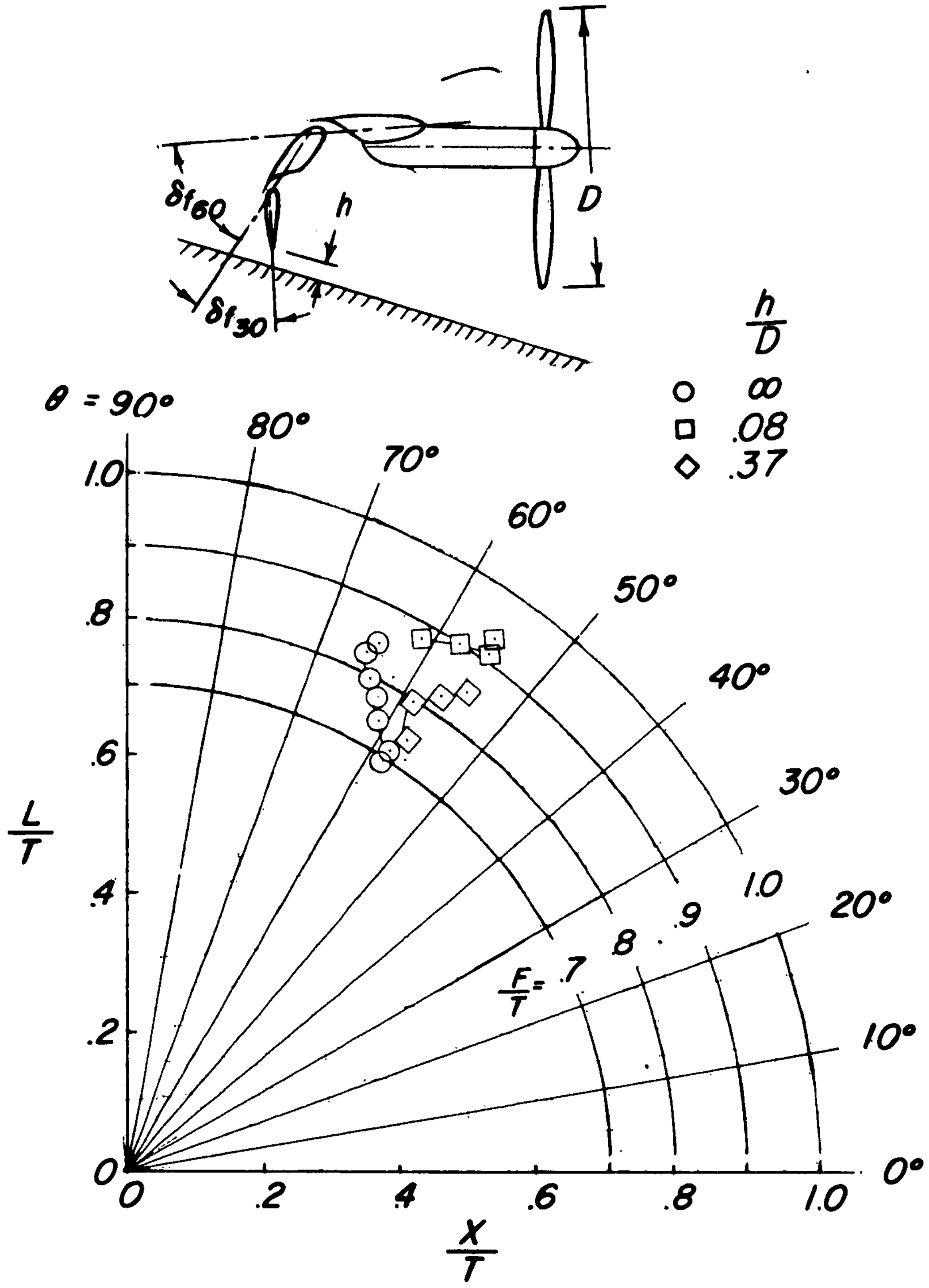


(a) Turning angle.

(b) Pitching moment.

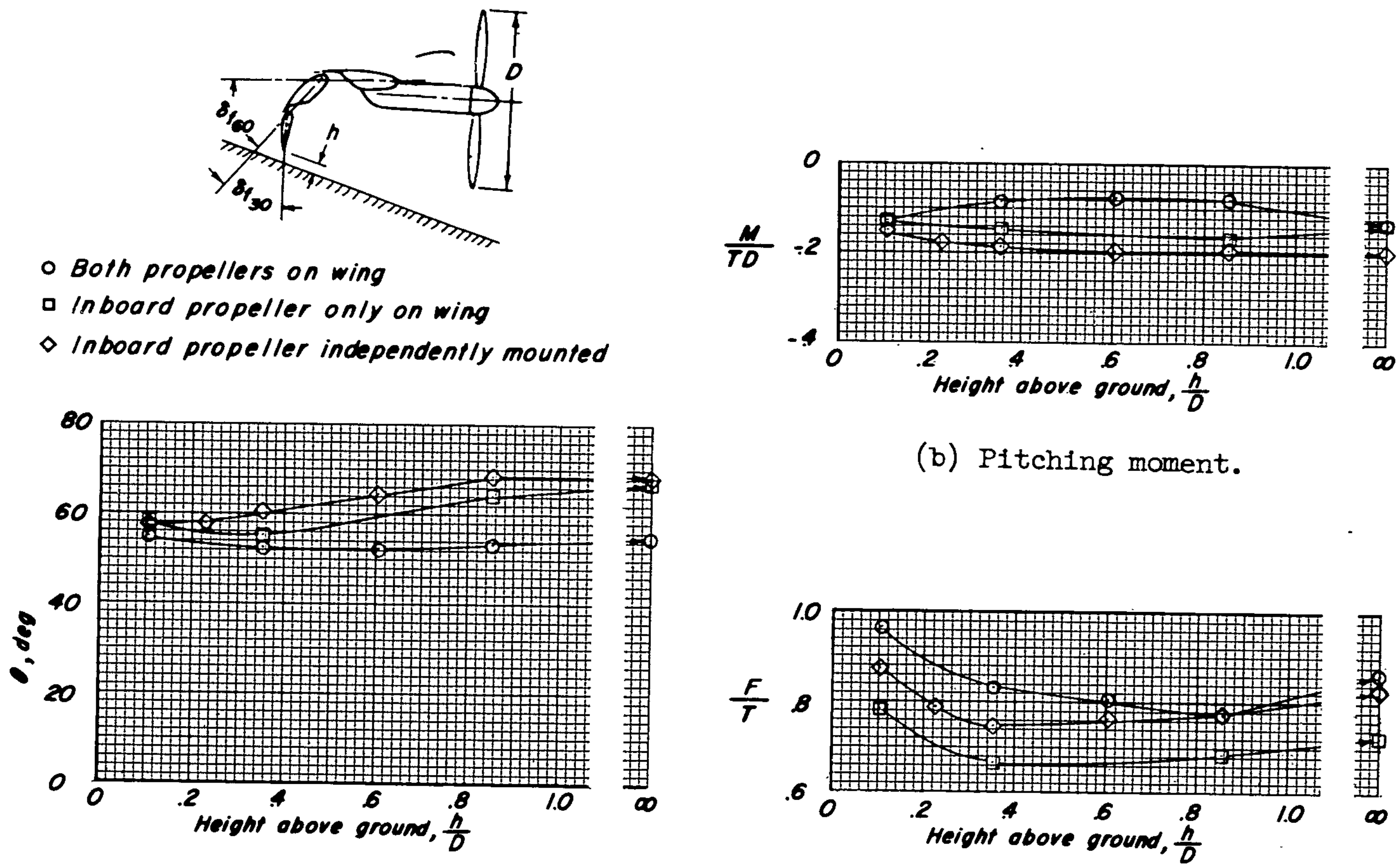
(c) Ratio of resultant force to thrust.

Figure 12.- Effect of ground on the variation of characteristics with slat deflection for the modified configuration. $\delta_{f_{60}} = 60^{\circ}$; $\delta_{f_{30}} = 40^{\circ}$; slat at position B; $i_w = 5^{\circ}$; $\frac{z}{D} = 0.100$.



(d) Summary of turning effectiveness. (δ_s is variable.)

Figure 12.- Concluded.

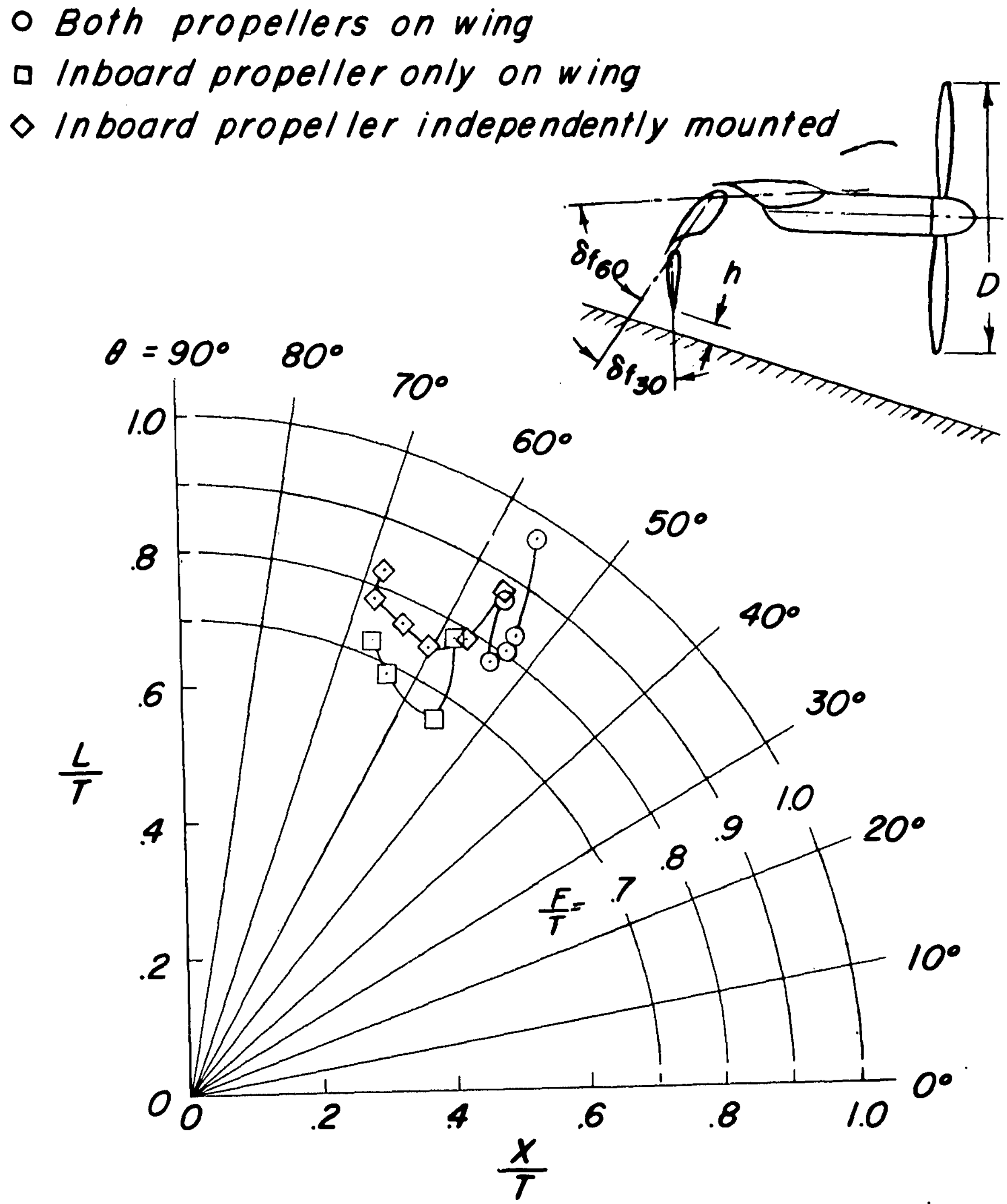


(a) Turning angle.

(b) Pitching moment.

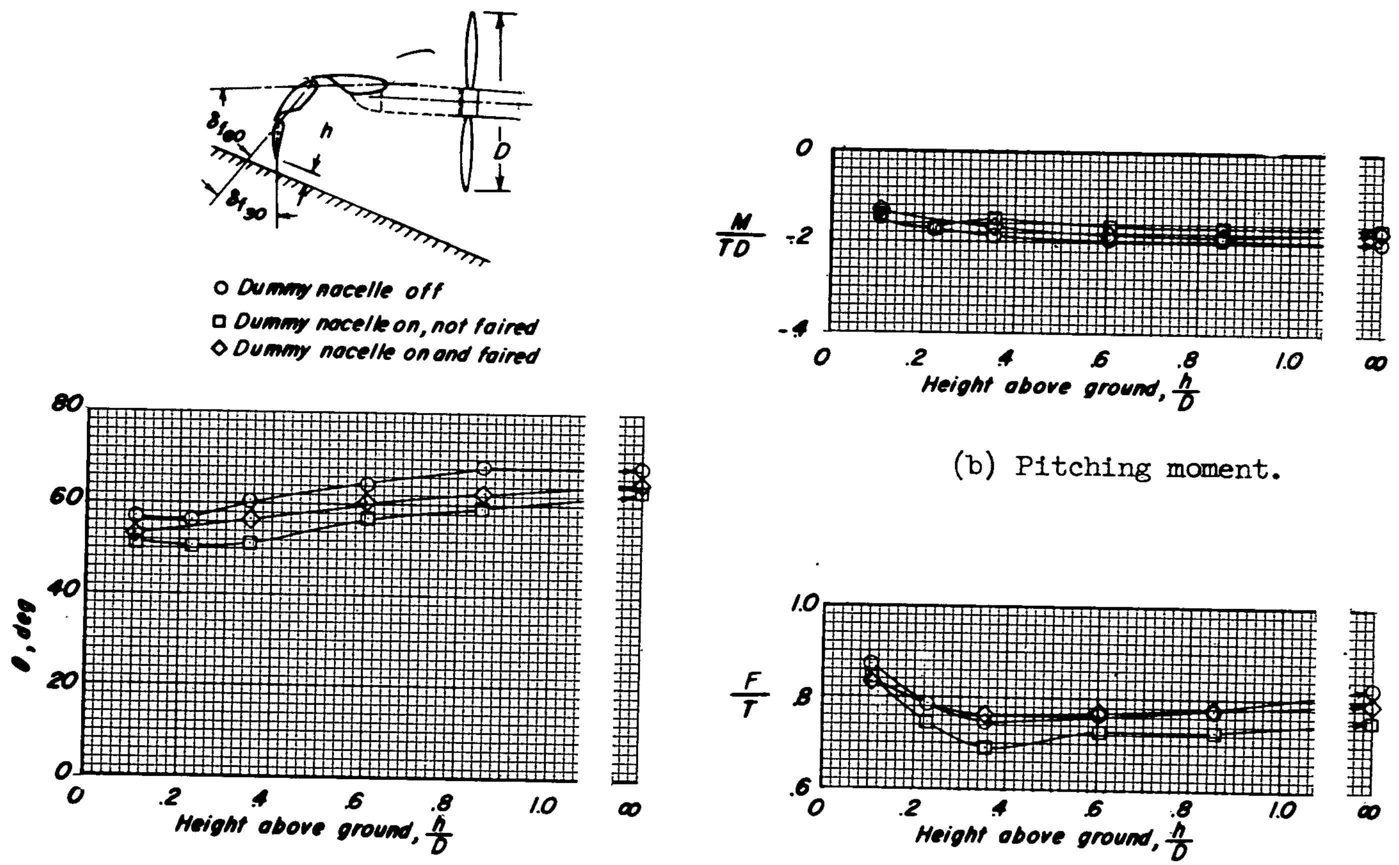
(c) Ratio of resultant force to thrust.

Figure 13.- Comparison of effect of height above ground on characteristics for one and two propellers. $\delta_{f_{60}} = 50^{\circ}$; $\delta_{f_{30}} = 40^{\circ}$; slat at position B; $\delta_s = 20^{\circ}$; $i_w = 5^{\circ}$; $\frac{z}{D} = 0.100$.



(d) Summary of turning effectiveness. $\left(\frac{h}{D}\right.$ is variable.$\left.\right)$

Figure 13.- Concluded.

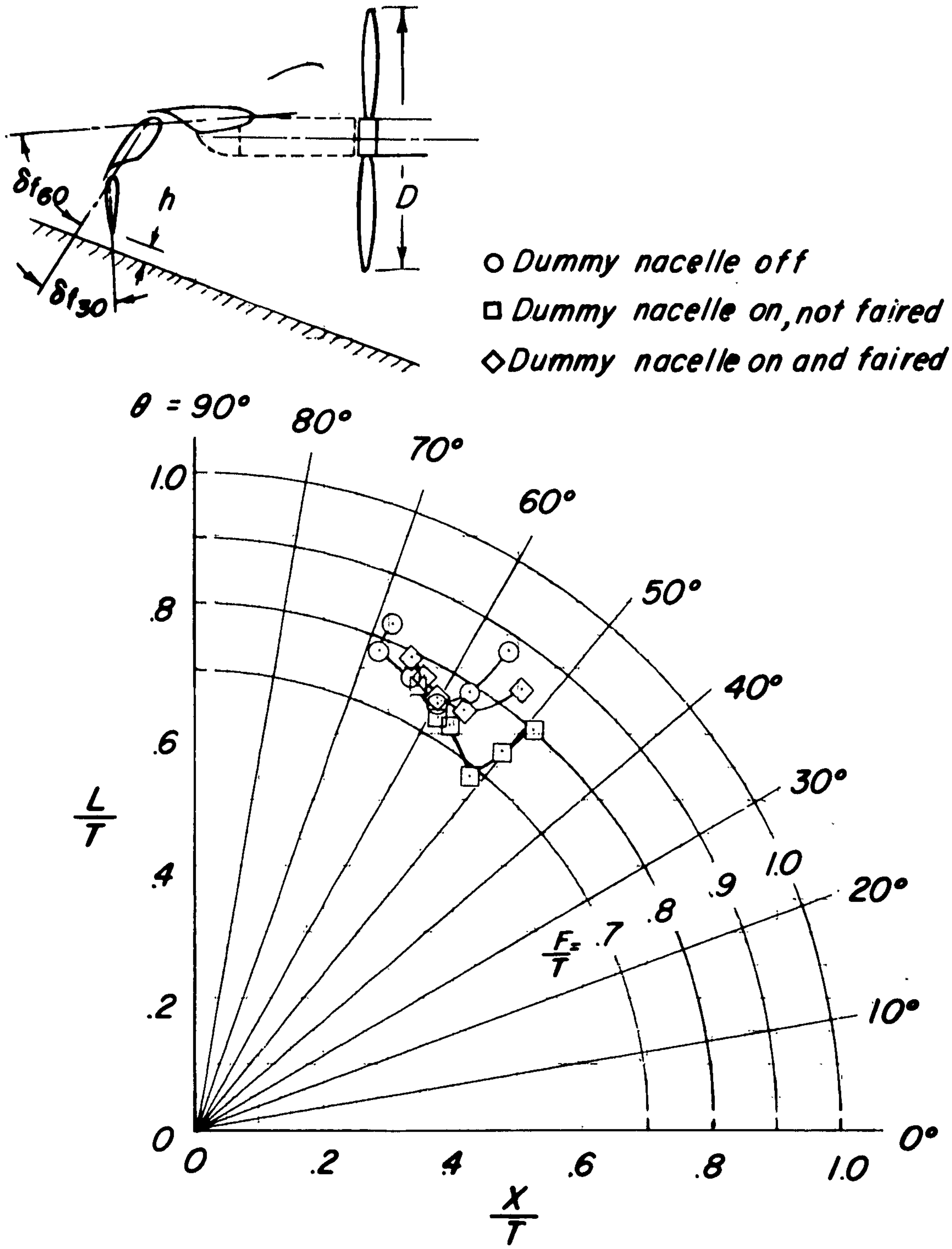


(a) Turning angle.

(b) Pitching moment.

(c) Ratio of resultant force to thrust.

Figure 14.- Effect of nacelle fairing on the variation of characteristics with height above ground. $\delta_{f_{60}} = 50^{\circ}$; $\delta_{f_{30}} = 40^{\circ}$; slat at position B; $\delta_s = 20^{\circ}$; $i_w = 5^{\circ}$; $\frac{z}{D} = 0.100$.



(d) Summary of turning effectiveness. $\left(\frac{h}{D}\right.$ is variable.$\left.\right)$

Figure 14.- Concluded.